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Offshore hydroelectric plant: A techno-economic analysis of a renewable energy source

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ABSTRACT

In a world where fossil fuel prices are subject to steep price hikes and where green house emissions are endangering the planet, dependence on non-renewable energy sources becomes more urgent. In this paper a technical feasibility and economic viability study of a new technology that utilizes hydroelectric power to tap the oceans' enormous energy reserve is presented. Called the Offshore Hydroelectric Plant, such an installation has an underwater powerhouse, the water from the turbines being discharged into a tail race sump (TRS). Power is generated when suitable head is created between the TRS and the sea, by leading the water out and allowing it to flow into giant troughs located in a vertical elevator building. Here, hoists raise the troughs carrying the excess water and empty them into an overhead tank (OHT). Water from the OHT is carried by penstocks to another powerhouse located at sea level. The plant utilizes the existing technologies of tidal plants, vertical ship lifts, and pumped storage schemes. Well-developed technologies of the offshore oil industry are utilized in fabricating the structures on shore, and towing them to location. An example demonstrates that a 104 MW plant could produce 569 GWh annually. Project investment costs are approximately $ 432 million and Levelized Electricity Costs $0.055/kWh.

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1. Introduction

In the quest for renewable energy, the oceans provide an enormous potential. There are primarily two types of ocean energy [1]: thermal energy from the sun's heat and mechanical energy from the tides and waves. Wave energy is created as winds pass over open bodies of water, transferring some of their energies to form waves which can be captured by wave conversion technologies to provide power. Wave energy [2] is considered as a major and promising renewable source. McFall [3] describes a system where a buoy riding the up and down motion of waves drives a piston which in turn draws sea water. The water is forced up a pipe to a storage tank placed at a height from where it is discharged through a turbine to generate electricity. Biteryakov [4]

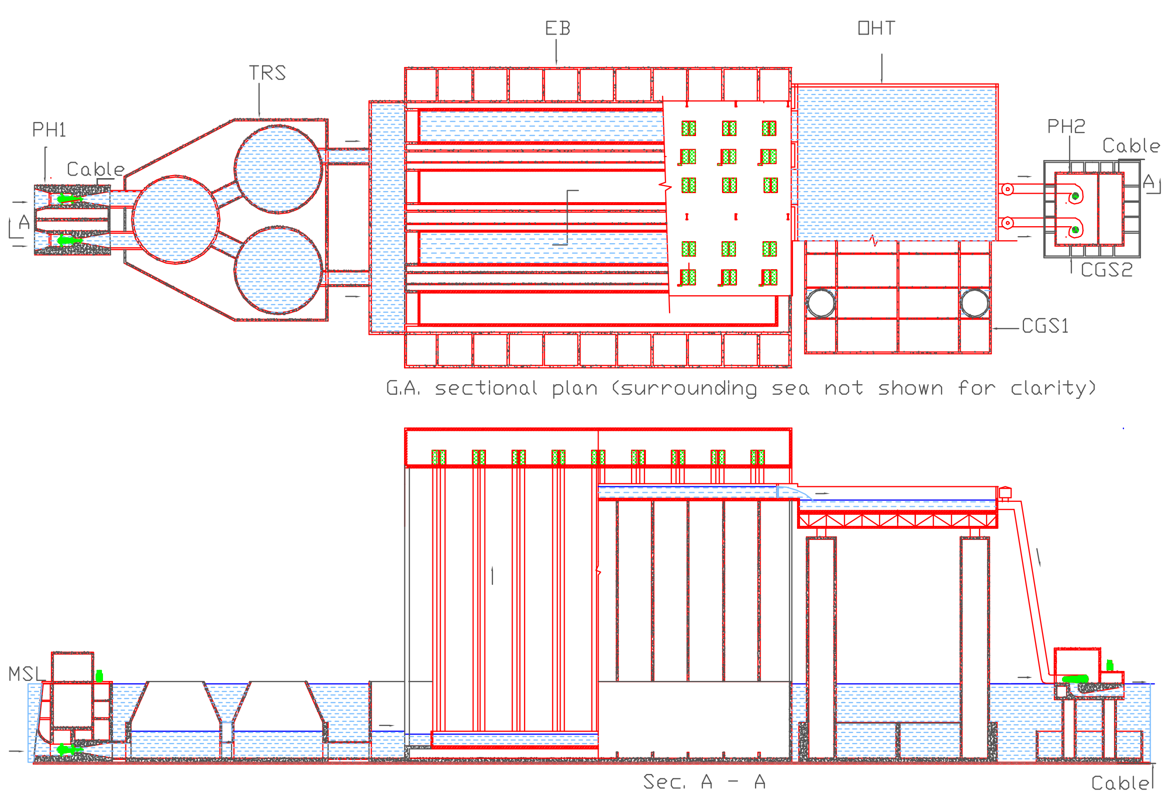

Fig. 1. G.A. plan and longitudinal section of Offshore Hydroelectric Plant.

discloses another electric power generation utilizing sea wave energy in which underwater tanks located at sea bed are allowed to fill with water The falling water is used to produce electric power and the waste water is lifted out to the surface by diaphragm pumps utilizing wave motion. Although a wide variety of wave energy converters [5] have been designed and tested, most of them have limited capabilities and are not yet developed to a commercially viable scale. Tidal plants utilize the vertical difference between high and low tides to generate electricity by creating a differential in the water levels on either side of a structure and then passing the water through turbines. However, for these plants to be economically viable they need to be located in regions with high tidal range Pontes and Falcao [6], also, since the tidal range is not constant the plants operate under a variable load and have a variable output. Even so, these schemes have high cost and high risks compared to other ways of generating low-carbon electricity. The 14 m tidal range of the Severn estuary is amongst the largest in the world. A feasibility study [7] has concluded that a tidal scheme in this estuary could cost as much as $544 billion. With current technology there is need for a plant that could extract energy from the ocean without having to depend on tides to create the head difference required for power generation. A scheme was developed whereby electric power was generated from an underwater powerhouse utilizing head created by difference in water level at the turbine inlet Nazir [8]. The waste water was collected in a deep sump and then pumped out to the surface by Geyser pumps. This required the plant to be located at great depth so as to create sufficient head for the Geyser pumps. These considerations have encouraged the search for an alternative cost-effective option which would be able to access the full potential of ocean energy. This paper proposes such a new technology called the 'Offshore Hydroelectric Plant' (OHP), and discusses its salient features with respect to design, construction and costs.

2. Overall concept

The overall aim was to demonstrate the viability of an offshore hydroelectric plant that could produce steady power. The present concept is based on tapping energy potential created by head differences to generate electricity. The configuration developed is shown in Fig. 1 and is called the offshore hydroelectric plant (OHP). It has the following salient features:

- An underwater Powerhouse building (PH1) similar to the one used at Shiwa Tidal Plant [9], comprising a turbine hall having turbines and other electro-mechanical equipment placed offshore in shallow waters and some distance from the shore line.
- A tail race sump (TRS) which acts as a basin to which water is allowed to flow from the turbines.
- A vertical elevator building (EB) with steel troughs and electromechanical hoisting equipment using vertical lifts to transport water, as is employed for raising barges in tanks in the vertical twin ship elevators of Strepy Thieu [10]. This method of raising water has been suggested as conventional pumps used in pumped storage hydroelectricity use more energy in pumping than is generated. A reason they are used only when low off-peak power is available.
- An elevated overhead tank (OHT) which stores water. This tank is analogous to the elevated reservoir of a pumped storage scheme which is used to convert stored gravitational potential energy into electrical energy. The tank is supported on a concrete gravity sub-structure (CGS 1), such as those used in oil and gas projects Collier [11].
- A second powerhouse (PH 2) located at sea level with turbines driven by water flowing from the (OHT) though penstocks. The powerhouse caisson is supported on a second concrete gravity sub-structure (CGS2).
- Submarine cable to transmit power to the shore based grid.

2.1. Working principle

Briefly, the stages of operation as to how the plant works is described with reference to the diagram shown in Fig. 1:

(1) Water is allowed to flow from the sea through the turbines located in PH1 to the TRS.
(2) Water from TRS is continuously removed and power is generated when a sufficient head develops due to falling level in the sump.
(3) Water from TRS flows into a pair of troughs located in an EB and transported vertically to an OHT, whilst another pair of empty troughs descend to base.
(4) Water from OHT is led by penstocks to another set of turbines installed in PH2 located at sea level to produce more electricity, which is then transported to the grid.
(5) This cycle is continuously repeated for maximum energy generation.

3. Preliminary design

It is impossible to record herein all the detailed steps leading to the final design. The more important steps may be divided into the following stages:

- Given the basic parameters such as availability of head and depth of sea adjacent to coastlines and places of power shortage, the first requirement is to establish the estimation of power to be generated and the number of units.
- Collecting field information in the areas of climatology, earthquakes, hydrological surveys, geotechnical surveys, wave modeling studies, tidal and current circulation studies, nautical studies, environmental studies, location of sources of construction material, and location of construction facilities preferably with marine experience.
- Selection of type of hydraulic turbines depending on specific speed, rotational speed, efficiency, overall cost, number of units and head. Similarly other mechano-electrical items such as generators, cranes, gates, valves, etc. are selected.
- Finalizing size of powerhouse PH1, depending on the number and size of turbines,
- Determining size and location of TRS depending on the length of draft tube, discharge from turbine, and head to be maintained.
- Determining size of troughs and their vertical travel time based on discharge from turbines and head to be maintained.
- Selecting size of friction sheave hoists, reduction gears, electric motors, cables, control room equipment, etc. based on load to be lifted and cycle time.
- Determining size of supporting structure of EB based on capacity of balanced funicular lifts to raise troughs carrying water to the required heights.
- Determining size of OHT and its supporting CGS1.
- Determining size of second powerhouse PH2 and its supporting CGS2.
- Determining section properties of various structural elements.
- Determining thickness of bed protection for marine gravity foundations Whitehouse et al. [13].
- Determining size and method of installation, for cables of collection system and transmission system.

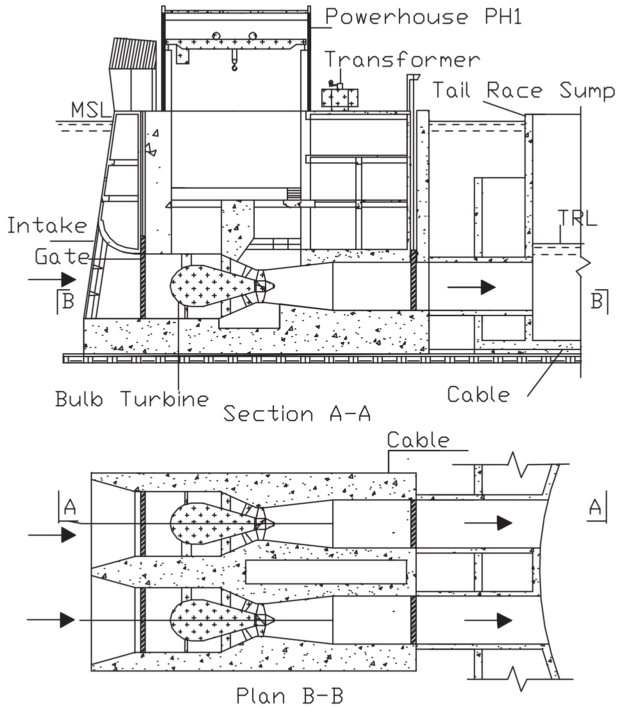

Fig. 2. G.A. plan and cross-section of Powerhouse PH1.

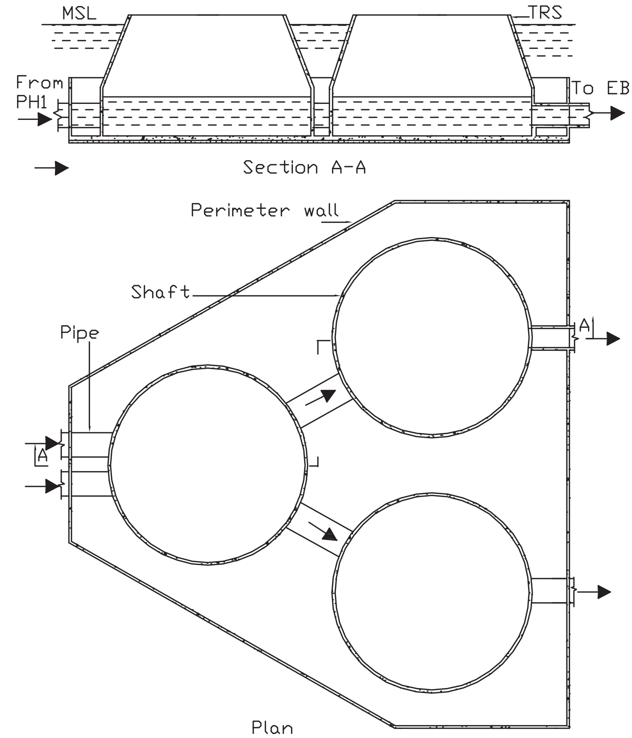

Fig. 3. G.A. plan and cross-section of Tail Race Sump.

4. Detailed plant design

4.1. PH1

The powerhouse is a reinforced concrete caisson which will be fabricated on-shore, floated out to site and placed on a prepared bed in shallow depths close to the shore. In general one turbine caisson will house two turbines (Fig. 2). Generally for low heads the most applied types of turbines are the Bulb turbines Jerome [14]. Sluice gates, valves and turbine governors control the flow of water and hence the output.

4.2. TRS

The tail race sump acts as a balancing reservoir and is designed to hold the water discharging from the turbines before being led into the elevator building. It is planned as a concrete caisson having a base raft with a perimeter wall. Shafts extend from the raft to above the sea level to hold the water (Fig. 3). The shafts are inter-connected by pipes to each other and to the elevator building so as to maintain the same level of water. The caisson is built in dry dock, floated out to site and installed on a prepared seabed. It is ballasted against floatation.

4.3. EB

The elevator building houses vertical lifts that help remove the excess water from the TRS by means of troughs that are raised and lowered vertically between the lower reach of the tail race sump and the upper reach of the OHT as shown in Fig. 4. The building structure comprises two independent balanced lifts. Operation of each pair of troughs is completely independent. The pre-stressed concrete structure consists of a watertight monolithic floor, four compartments for troughs, two cellular side compartments for buoyancy, an intake chamber and a steel platform for machinery to maneuver the troughs. The concrete gravity structure may be provided with skirts depending on soil conditions. Troughs and the reaches of water are fitted with vertical gates. The building is built in dry dock, floated out to site and installed on a prepared seabed. It is ballasted against floatation. The mass of each water-filled trough is balanced by a similar trough acting as a counter-weight. The troughs are connected by a system of cables. The mode of suspension of the troughs is shown in Fig. 4. Sheaves help distribute the load and reduce tension in the cables. The cables pass over the drum of a friction hoist of the Koepe type. This allows one trough to rise as the other trough is lowered. The troughs are set in motion by a series of winches driven by a low-speed reduction gear connected to a high-speed gear that is driven by a motor as shown in Fig. 5. Winches are linked by a rigid synchronous loop. Since the weights of the troughs are equal, the hoist has to overcome the load of water in one trough. Each trough is equipped with an oleo-hydraulic system which spreads the strains in the cables uniformly, Strepy Thieu [10]. Electrical and mechanical braking systems are used. Size of the troughs and their travel time are determined on discharge from turbine and head to be maintained. A control room houses the computers and micro-processors which carry out the maneuvering of the troughs and the gates.

4.3.1. Description of maneuvering

The following operations are necessary to overcome the difference in level for the troughs going from the downstream reach to the upstream reach:

- Troughs are blocked in downstream position. Watertight seal is applied. The downstream gates of the troughs and the reach are raised together so that water flows into the troughs.
- Once the troughs fill with water, the gates are lowered, watertight seals are released and the troughs are raised.

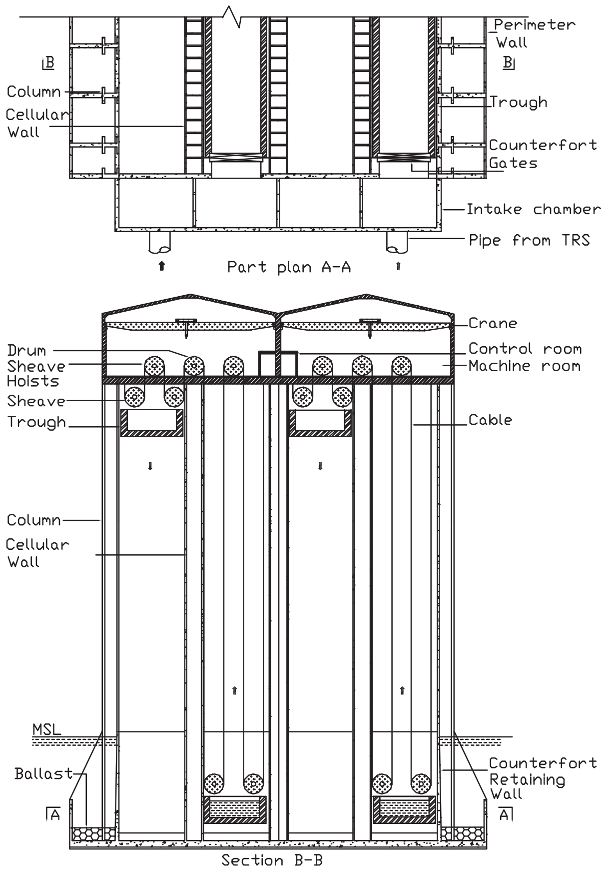

Fig. 4. Cross-section of Elevator Building.

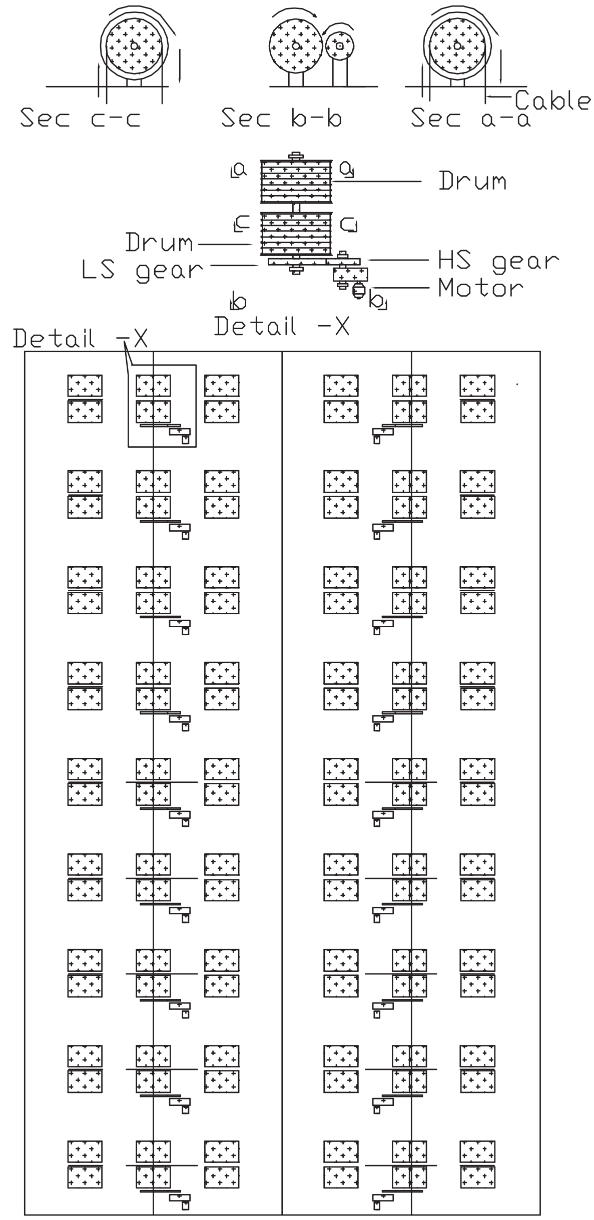

Fig. 5. Schematic plan of machine room of EB with arrangement of winch drives.

- On troughs reaching the upper reach, watertight seal is applied, gates on troughs and upper reach are opened and water flows into the OHT.
- The gates are closed, seals released, empty troughs are lowered and the cycle is repeated.

4.4. OHT

The tank's capacity is designed for storage from the water flowing from the troughs so as to provide a continuous flow to the turbines. The tank is planned on a steel plate construction with orthotropic plates. It rests on steel trusses which transfer the load to the supporting shafts of the CGS. It is fabricated at the construction yard and installed by the float over technique as was done for the Mallampaya CGS, Collier [12]. Penstocks lead the water away from the tank to the turbines (Fig. 6). Surge tank may be required for greater height differences.

4.5. CGS 1

The main functional requirement of the CGS1 was to support the OHT. The advantages of the CGS VSL Int [15] lie in the economy of materials used, in the fact that it is easy to make the structure buoyant in the construction stage and for towing. The design solution for the CGS1 consists of a cellular concrete caisson; the structure has a base slab, perimeter walls, number of cells and multiple cylindrical shafts for supporting the OHT (Fig. 6). The CGS is built in dry dock, floated out to site and installed on a prepared seabed. It is ballasted against floatation.

4.6. PH2 and CGS2

In this powerhouse the turbine is set so that water discharges into the sea (Fig. 7). As the turbine will operate under medium head (30–150 m) and also require medium quantities of water, the recommended type of reaction turbine would be a Francis Turbine, Lal [16]. The construction features of this powerhouse are similar to those described for PH1 except that the base level of this powerhouse is much above the sea bed. Thus a CGS2 is required to support the powerhouse and transfer the loads to the sea bed (Fig. 8).

4.7. Grid connection

The electrical system integrates AC power from individual turbines and transforms voltage from 11 kV to 132 kV for export via submarine cable to onshore substations. Submarine cable forms a major component of construction costs and HVAC is suggested as it is the most economical option for distances shorter than 50 km Green et al. [17].

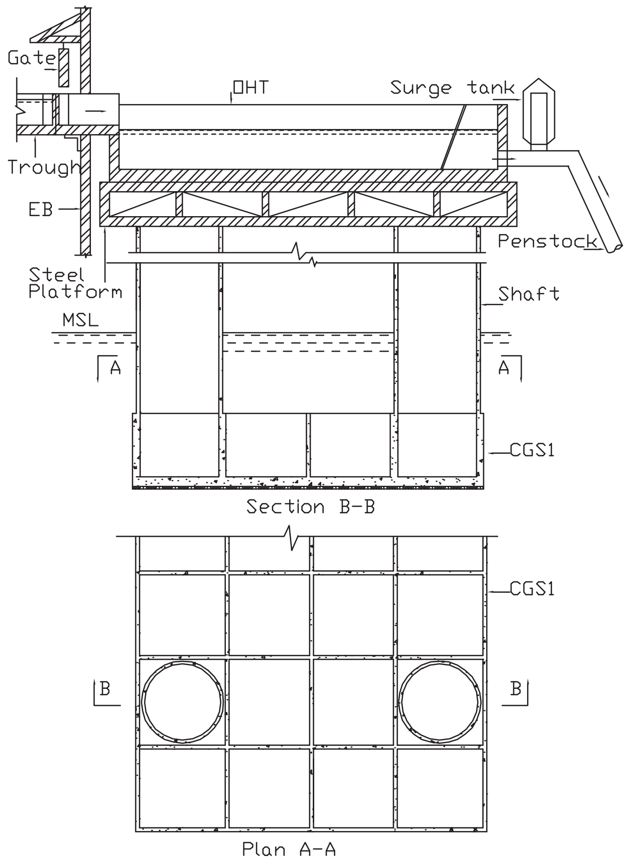

Fig. 6. Part plan and cross-section of Concrete Gravity Substructure CGS 1 for Overhead Tank.

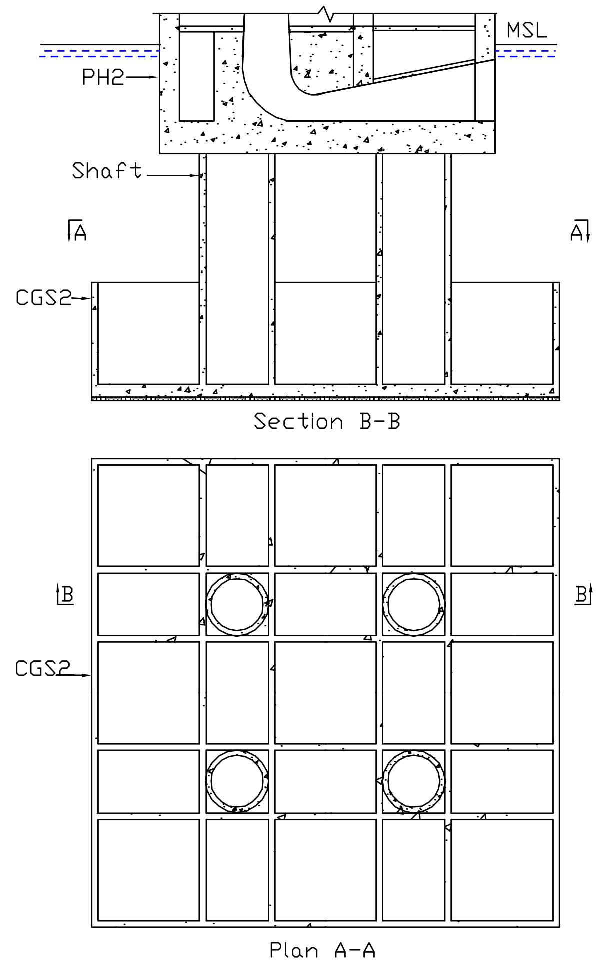

Fig. 8. G.A. plan and section of Concrete Gravity Substructure CGS 2 for PH 2.

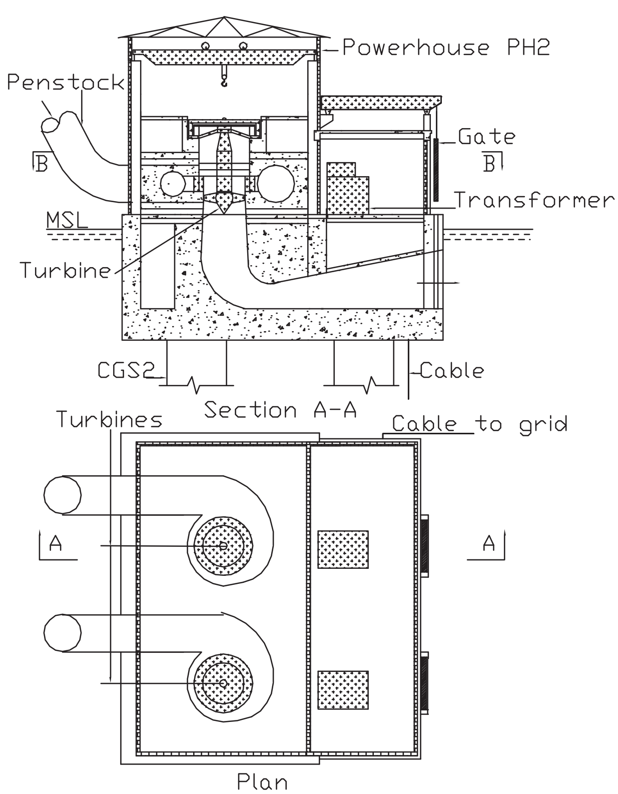

Fig. 7. G.A. plan and cross-section of Powerhouse PH 2.

5. Example

The offshore locations where power could be developed economically are vast because the technology does not need a strong tidal energy concentration. As a practical design application, conceptual design and cost estimates are made for an OHP located 16 km from shore where the depth of water is approximately 25 m. The mean tidal range between successive high and low tides is taken as 1.0 m. A typical layout for one module would be as shown in Fig. 1. It is proposed to have two modules, each with an installed capacity of 52 MW, giving a total plant capacity of 104 MW.

5.1. PH1

Each powerhouse caisson has two turbines as shown in Fig. 2. The mean available head is based on the water level in the TRS. Assume mean high water level (MHWL) as 707.5 m, mean low water level (MLWL) as 706.5 m and TRS full supply level (FSL) as 691.5 m. This gives a maximum head of 16 m. The rated head is taken as 15.28 m and the rated flow 33 cumec per unit (based on quantity and speed at which water is removed by troughs in TRS). Based on this input, the recommended type from EXCEL PROGRAM for Turbine Generator selection Hydro Help1 [18] is a mini bulb turbine, having a throat diameter of 2.22 m. The power generated by each turbine is 4.3 MW and the total for two turbines is 8.61 MW.

The powerhouse building for the two turbines comprises the turbine hall and auxiliary bay. The two turbines are spaced at 9 m

centers. The caisson is 26.5 m × 15 m × 25 m high. The superstructure for the turbine hall is 26 m × 13 m × 8 m high. A conical draft tube (sill level 684.8) having an outlet diameter of 4.5 m discharges the flow from the turbine to the tail race sump. Costs are approximate and calculated based on prevailing rates.

5.1.1. PH1 civil and equipment cost $ million

Concrete 3790 m³ @ $550/m³	=2.08
Crushed rock for bed laying 148 m³ @ $25/m³	=0.01
Turbines 8.61 × 10³ kW @ $700/kW	=6.02
Sub-total	=8.11
Transportation and erection @ 4%	=0.32
Total cost of **PH1**, C_{ph1}	=8.43

5.2. TRS

The tail race sump is designed as a concrete gravity structure and caters for the flow from two turbines. The level of water in the tail race sump is maintained at approximately 4 m above the turbine center line, so as to obtain a gross head of 16 m below mean sea level (MSL) for generation. Approximate size of TRS is obtained as follows. There are 4 troughs in elevator building, each pair completing a return journey in 372 s respectively. Each trough has an area of 1535 m^2, water height of 4 m and volume=6138 m³. Let area of TRS=5 × 1535=7675 m^2. Minimum depth of water in TRS above turbine center line=4 m. Then volume of water in TRS=4 × 7675=30,700 m^3. Assume that after 186 s, one pair of troughs has just cleared the bottom reach and the second pair is at top. Now water entering TRS in 186 s=186 × 33 × 2=12,276 m^3 and water removed from TRS by two troughs=2 × 6138=12,276 m^3. Then total water in TRS=30,700+12,276 − 12,276=30,700 m^3. Depth of water in TRS=30,700/7675=4 m. Similarly, after another 186 s, water entering and leaving the TRS is the same, and the depth of water is 4 m. The structure provided has a trapezoidal base raft having an area of 8835 m^2, a perimeter wall 9 m high. To keep the size of storage shaft within practical limits, three storage shafts are provided, each with internal diameter 57 m and height 27 m. A typical layout is shown in Fig. 3.

5.2.1. TRS civil cost $ million

Concrete 19,738 m³ @ $ 550/m³	=10.85
Crushed rock for bed laying, 2650 m³ @ $ 25/m³	=0.66
Subtotal	=11.51
Transportation and erection @ 4%	=0.46
Total cost of **TRS**, C_{trs}	=11.97

5.3. EB

The EB is designed for 4 troughs each of 6138 cum capacity to transport water vertically from the lower reach of the TRS into an OHT, the height difference being 100 m. The supporting structure of the lift is made of pre-stressed concrete. Its overall dimensions are 130 m long, 114 m wide and approximately 130 m high. Its base is 25 m below MSL. A typical cross-section is shown in Fig. 4. Cellular pre-stressed concrete walls 4.4 m wide, 110 m high, separate the four number 17 m wide chambers. The two outer walls exposed to the sea are designed as counterfort retaining walls, with 12 m depth buttresses spaced at 12 m centers. End walls approximately 1 m thick are designed to span horizontally across the cellular walls. Perimeter walls are 10 m high. A 12 × 81.2 × 27 m high intake sump is provided at one end of the building. The troughs and the reaches of water are fitted with vertical gates. The bottom level of trough is maintained at 20 m below MSL The 118 m long, 13 m wide, steel troughs are designed as a self-supporting structure. It provides for a water depth of 4 m and freeboard of 1 m. Trough construction is an orthotropic plate with the main beams 6.5 m high and 1.5 m wide. Concrete ballast is used to increase self-weight. The troughs hang evenly from 72 cables on each side. The troughs are connected by cables that are guided over sheaves and pass over the top of a drive wheel of a friction sheave hoist, as shown in Fig. 4. A covered machine room 130 × 81 × 25 m high is located 90 m above MSL. It houses all the mechanisms (motor, reduction gear, and winch) and the operating and control stations of the two independent lifts for each pair of troughs.

5.3.1. Winch drive

The mass of the troughs counterbalance one another. The drive system is designed to overcome the 4 m depth of water in one trough. In the machine room, the mechanisms are divided into 9 groups for lifting/lowering two troughs in balance. A typical arrangement is shown in Fig. 5. Each group consisting of a friction sheave hoist having two drums on a common shaft driven by a low-speed reducing gear. This is coupled to a high-speed reducing gear driven by a 1000 rpm AC motor. Diameter of drum and sheaves is 4.8 m. 4 cables of 85 mm diameter are passed over each drum.

5.3.2. HP required

To determine HP of the hoist system using an AC motor and hoisting two troughs in balance to overcome 100 m height difference, assume rope speed 1.5 m/s, accel 0.15 m/s², dec. 0.15 m/s².

Hoist duty cycle time:

Accel to full speed t_a=10 s; travel at full speed t_v=56 s; dec to rest t_r=10 s. Rest period, t_d=214 s.

Total duty cycle time;

Travel to top 76 s; Seal applied 10 s; Open gate 10 s; Empty trough 70 s; Close gate 10 s; Release seal 10 s; Descent 76 s; Apply seal 10 s; Open gate 10 s; Fill trough 70 s; Close gate 10 s; Release seal 10 s.

Then total time for one return journey=372 s.

Two troughs emptying 2 × 6138 cum in 372 s gives a flow rate of 33 cumec.

Weight of water in one trough 6138 t; load on one side 6138/4=1536 t; Load shared by one cable=1538/72=21.2 t, and load shared by 8 cables=170 t.

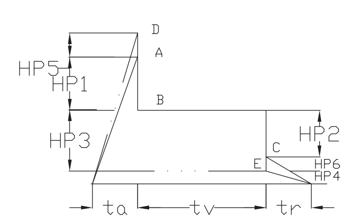

Fig. 9. Plot of duty cycles – power vs time.

Weight of trough = 7365 t; and load on one side = 7365/4 = 1841 t; load on one cable = 1841/72 = 25.6 t, and load shared by 8 cables = 204 t.
Unbalanced load due to water level difference of 4 m is 6138 t; and load shared by 8 cables = 170 t
Weight of 1 cable = 3 t and for 8 cables = 24 t
Checking rope slippage;
Weight of loaded trough on 8 cables;
T1 = 170 + 204 + 24 = 398 t.
Weight of empty trough and 8 cables; T2 = 204 + 24 = 228 t.
Then T1/T2 = 398/228 = 1.74 < 1.8.
Effective weight of drum = 70 t
Then total suspended load = (70 + 2 × 204 + 170 + 24) = 672 t
Based on formulas from Mining Eng Handbook Hartman [19] the HP at different locations on duty cycles see (Fig. 9) are as follows; $P_1 = 182$ hp: $P_2 = -182$ hp;
$P_3 = 3060$ hp; $P_4 = 340$ hp; $P_A = 3582$ hp; $P_B = 3400$ hp;
$P_C = 3218$ hp; $P_5 = 322$ hp;
$P_6 = -322$ hp; $P_D = 3904$ hp; $P_E = 2896$ hp. Then root mean square power for AC motor is given in Eq. (1)

$$P_{rms} = \sqrt{\frac{P_D^2 t_a + P_B{}^2 t_v + P_E{}^2 t_r}{0.5t_a + t_v + 0.5t_r + 0.25t_d}}\ \text{hp} \tag{1}$$

$$P_{rms} = \sqrt{\frac{3904^2 \times 10 + 3400^2 \times 56 + 2896^2 \times 10}{0.5 \times 10 + 56 + 0.5 \times 10 + 0.25 \times 214}} = 2725\ \text{hp} = 2030\ \text{kW}$$

Then for 2 × 9 stations, power consumed = 2 × 9 × 2030 = 36,540 kW. Approximate energy consumption per duty cycle is given by Eq. (2):

$$E = \frac{0.745 \times P_B \times (t_a + t_v)}{3600 \times 0.9}\ \text{kWh/trip} \tag{2}$$

$$E = \frac{0.745 \times 3400 \times (10 + 56)}{3600 \times 0.9} = 52\ \text{k Wh/trip}$$

5.3.3. Civil and equipment cost $ million

Concrete 92,621 m³ @ $ 550/m³	= 50.94
Crushed rock for bed laying, 4582 m³ @ $25/m³	= 0.11
Steel superstructure, troughs, 19,574 t @ $1500/t	= 29.36
Friction hoists, motors, etc., 18 no @ $2 × 10⁶	= 36.0
Sub-total	= 116.41
Transportation and erection @ 4%	= 4.64
Total cost of **EB**, C_{eb}	= 121.05

5.4. OHT

The overhead tank is designed as a steel structure and caters for the flow from two turbines. The tank is located at a height above sea level so that the highest level of water in the tank is lower by 1 m than the bottom level of troughs (+80 m). The level of water inside the OHT is maintained at approximately 4 m above the top of penstock, so as to obtain a gross head of 79.5 m above MSL for generation (see Fig. 1). Approximate size of OHT is obtained as follows. There are 4 troughs. Let area of OHT = 4 × 1535 = 6140 m². Let minimum depth of water above top of penstock in OHT = 4 m. Then volume = 4 × 6140 = 24560 m³. Assume that after 186 s, one pair of troughs has just cleared the bottom reach and the second pair is at top. Now water leaving OHT in 186 s = 2 × 33 × 186 = 12,276 m³ and water entering OHT from two troughs = 2 × 6138 = 12,276 m³. Then total water in OHT = 24,560–12,276 + 12,276 = 24,560 m³ and depth of water in OHT = 24,560/6140 = 4 m. After another 186 s, water leaving OHT = 2 × 33 × 186 = 12,276 m³, and water entering OHT from two troughs = 2 × 6138 = 12276 m³. Then total water in OHT = 24,560–12,276 + 12276 = 24,560 m³. Then depth of water = 24,560/6140 = 4 m. Two penstocks (3 m dia) lead the water away to PH2. The quantity of steel for tank is approximately (6140 m² @ 1.5 t/m²) = 9210 t. The tank is supported on a steel platform formed of a tubular space structure spanning the four support shafts of CGS1. A typical section is shown in Fig. 6. The quantity of steel for the supporting structure is approximately (6140 m² @ 1 t/m²) = 6140 t.

5.4.1. OHT civil cost $ million

Steel tank 9210 t @ $1500/t	= 13.81
Steel platform 6140 t @ $1500/t	= 9.21
Subtotal	= 23.02
Transportation and erection @ 4%	= 0.92
Total cost of **OHT**, C_{oht}	= 23.94

5.5. CGS1

The CGS1 is designed to support the steel structure of the OHT. It is a reinforced concrete caisson having a base slab with dimensions of 53.6 m × 81.6 m and approximately 1 m thick with a 10 m high perimeter wall. It has 20 compartments formed by internal walls spaced at 13.6 m centers. Four shafts of 12 m internal diameter and 92 m height provide support to the OHT. A typical plan and section is shown in Fig. 6. The shafts are constructed up to 4 m above sea level and the CGS floated out and placed on the prepared sea bed. The steel structure is placed over it by float over method and the shafts along with the OHT raised to the required height.

5.5.1. CGS1 civil cost $ million

Concrete 15,350 m³ @ $550/m³	= 8.44
Crushed rock for bed laying, 1328 m³ @ $25/m³	= 0.03
Subtotal	= 8.47
Transportation and erection @ 4%	= 0.34
Total cost of **CGS1**, C_{cgs1}	= 8.81

5.6. PH2

Each powerhouse caisson has two turbines. Taking MHWL as 707.5 m, MLWL as 706.5 m and FSL of OHT as 786.0 m, this gives a maximum head of 79.5 m. Rated head is taken as 76.72 m and quantity of water available at this head is 33 cumec per unit. Based on this input, the recommended type from EXCEL PROGRAM for Turbine Generator selection Hydro Help1 [18] is a vertical axis Francis Turbine with steel casing having a throat diameter of 2 m. The power generated by turbine is 21.93 MW, and for two turbines it is 43.85 MW.

The powerhouse building comprising the turbine hall and auxiliary bay is built up of a module housing two turbines. Two steel penstocks of 3 m diameter lead the water from the OHT to the turbines. The two turbines are spaced at 10 m centers. A typical arrangement is shown in Fig. 7. The concrete caisson is $24.4 \times 23.4 \times 9$ m high. The superstructure for the turbine hall is $24 \times 15 \times 9$ m high. Crane girder is designed for a 60 t crane. A conical draft tube having an outlet diameter of 4 m discharges the flow from the turbine to the sea. The sill level of the draft tube is 6.7 m below MSL.

5.6.1. PH2 civil and equipment cost $ million

Concrete 3480 m^3 @ $\$550/m^3$	=1.91
Steel (penstocks, etc.) 246 t @ $1500/t	=0.37
Turbines 43.85×10^3 kW @ $700/kW	=30.69
Sub-total	=32.97
Transportation and erection @ 4%	=1.32
Total cost of **PH2**, C_{ph2}	=34.29

5.7. CGS2 for power house 2

This CGS is designed to support the Power house caisson. It is a reinforced concrete caisson having a base slab with dimensions of 32.8 m × 32.8 m and approximately 1 m thick with a 9 m high perimeter wall. It has 20 compartments formed by internal walls spaced at 8.8 m centers. Four shafts for supporting PH2 are 3.7 m internal diameter and 16.2 m high. CGS is placed on the prepared sea bed. A typical arrangement is shown in Fig. 8.

5.7.1. CGS2 civil cost $ million

Concrete 2673 m^3 @ $\$550/m^3$	=1.47
Crushed rock for bed laying, 1076 m^3 @ $\$25/m^3$	=0.03
Subtotal	=1.5
Transportation and erection @ 4%	=0.06
Total cost of **CGS2**, C_{cgs2}	=1.56

5.8. Grid connection

Power from the generators in the four power houses is collected by a local 11 kV system which is then transformed up to 132 kV using conventional AC transformers and transmitted to mainland via a 16 km long submarine cable. The cost of cable is taken based on Western Offshore Grid UK govt. Concept study [20].

Cable Cost $ million	
Cost of 16 km long 132 kV ac submarine cable @ $476,000/km	=7.62
Cost of 224 m long 11 kV in row cable $ 187,000/km	=0.04
Fixed mobilization	=0.66
Cost of transformers	=0.51
Total cost of Grid Connection, C_{gr}	=8.83

5.9. Other costs

For other costs $C_{o,}$ a lump sum figure of $ 3.0 million has been taken to include for design and advance planning.

6. Costs of OHP

Besides the technical feasibility of OHP generation, the economical aspects also need to be considered. This will depend on the following three aspects: the overnight construction costs of the project ($/kW), the levelized electricity costs ($c/kWh) and the capacity factor.

6.1. Overnight construction costs

These are the capital costs of the project if it could be constructed overnight (and do not include interest). They are determined by dividing the total construction costs C_c by the plant capacity $P_{cap.}$ The total construction costs for two modules can be determined by adding the separate costs and is given in Eq. (3):

$$C_c = \{2(C_{ph1} + C_{trs} + C_{eb} + C_{oht} + C_{cgs1} + C_{ph2+} C_{cgs2}) + C_{gr} + C_o\}$$
$$C_c = \{2(8.43 + 11.97 + 121.05 + 23.94 + 8.81 + 34.29 + 1.56) + 8.83 + 3\}10^6 = \$431.9 \times 10^6$$
$$P_{cap} = \text{Power from two modules} = 2(8.61 + 43.85) = 104.5\ \text{MW}. \tag{3}$$

Then overnight construction costs are given in Eq. (4):

$$\frac{C_c}{P_{cap}} = \frac{431.9 \times 10^6}{104.5} = \$4.13 \times 10^6/\text{MW}. \tag{4}$$

6.2. Capacity factor

Unlike tidal plants, the design of OHP allows for continuous production of energy for most of the year. Some existing hydro plants that are run as base load due to continuous and abundant supply of water have a high capacity factor that is comparable to thermal plants. Itipu plant for example has a capacity factor of 77% Jcmiras, [21]. In another comparison, the Vertical Ship Lift at Three Gorges Dam is designed to operate for 7370 h/yr, Kreb et al. [22]. Thus a reasonable assumption has been made that the plant runs for 7008 h/yr out of a total of 8760 h/yr, giving a capacity factor of 0.8.

6.3. Annual generation

Using a capacity factor of 0.8, the yearly energy output E_a per kW of plant capacity would be with a generator efficiency of 0.95 Lund [23], where generator efficiency is a dimensionless parameter representing the amount of energy after being through the generator, divided by the energy coming though the turbines.

$E_a = 1 \times 24 \times 365 \times 0.8 \times 0.95 = 6657$ kWh

Power available from plant $= 104.5 \times 10^3$ kW

The overall energy conversion of the plant is the net energy produced by the generators less the energy consumed by the friction hoist motors:

$$\text{Energy from plant} = 104.5 \times 10\hat{3} \times 6657 = 695,657 \times 10\hat{3}\ \text{kWh/yr}.$$

Energy used by 2×9 no. winch drives, with each motor consuming 52 kWh/trip. In 7008 h, the troughs complete 67,819 trips based on 372 s/trip. Then, for two modules, total power

consumed by winch drives $= 2 \times 18 \times 52 \times 67{,}819 = 126{,}957 \times 10^3$ kWh/yr

$$\text{Net energy from plant} E_{net} = 695,657 \times 10\hat{3} - 126,967 \times 10\hat{3} = 568,700 \times 10\hat{3} \text{ kWh/yr}.$$

6.4. Levelized electricity costs

The levelized electricity costs represent the generating costs after initial investment. They are given by dividing the total construction costs in a lifetime C_{cl} by the total net energy produced during this lifetime E_{nl}. For this example, the simplified Lifetime Cost of Energy is calculated by inserting the relevant data in the energy calculator NREL-Energy Analysis. [24]. The calculations are based on the following formula given in Eq. (5).

$$\text{sLCOE} = \{(\text{overnight capital cost} \times \text{capital recovery factor} + \text{fixed O \& M cost})/8760 \times \text{capacity factor}\} \quad (5)$$

where CRF is the ratio of constant annuity to the present value of receiving the annuity for a given length of time. The following data has been used; Capital cost = 4130 \$/kW; Plant life = 40 years; Fixed O& M cost = 21 \$/kW-yr Taken as 0.5% of plant cost, Baker [25]; Discount rate 5%, Capacity factor 80% From sLCOE calculator NREL; sLCOE = 3.7 \$c/kWh. Allowing for net energy from plant, sLCOE = .5 \$c/kWh. It may be noted that the cost of energy has been calculated using a simplified model of a generic OHP and should be taken as illustrative only.

7. Results and discussions

7.1. Construction costs

From the previous chapter it can be concluded that OHP has high investment construction costs. However, this price will continuously drop over the next ten years with increased installed capacity, as a result of technological improvements, economics of scale and volume production. The levelized electricity costs on the other hand are on the low side. Renewable energy generated at this cost would be commercially very attractive.

7.2. Cost comparison

A revealing cost comparison can be made with the Horns Rev wind farm project in Denmark, Chary, [26], located 15 km offshore at a depth of 10 m. It has an installed capacity of 160 MW and was completed in 2002. The cost per MW of installation was € 2.1 million (\$3.07 m) and tariff € 82/MWh (\$c 11.97/kWh). In another comparison, estimates from Accelerating Marine Energy [27] put the levelized cost of energy for offshore wave at 38–48 p/kWh (\$c 61–77/kWh), and for tidal at 29–33 p/kWh (\$c 46–53/kWh).

7.3. Flow rate

It will be noted from the example that the flow rate is one of the main governing factors for the output of power generated, both from PH1 and from PH2. The flow rate is dependent on: (a) quantity of water transported by troughs; and (b) time taken for each return trip which, in turn, depends on the speed at which the troughs are hoisted.

7.3.1. The size of troughs to transport water would depend on practical considerations

The largest trough in use is at 3 Gorges Dam [22] and has a capacity of 7500 m^3.

7.3.2. As regards speed of travel, a conservative value of 1.5 m/s has been assumed

In the mining industry, winding speeds unto 15 m/s are common in deep shafts [28]. The world's largest single AC friction hoist with a payload of 45 t and hoisting speed of 18.3 m/s from 1000 m has been installed at Mosaic Potash Esterhazy, K2 Mine [29].

7.4. Head difference

Head of water available is another important parameter for determining the quantity of power produced. In the present example, the height of OHT and the TRS is determined so as to provide a head of approximately 80 m for turbines in PH2. Present technology for offshore CGS permits much taller structures to be built. The offshore CGS for the Troll Platform is over 300 m tall [30].

7.5. Scale up

Thus, it can be seen that this plant can be scaled up to produce even larger quantities of power. An array of such modules, electrically coupled would allow for expansion to power plants with capacities of 1000+MW. These would provide high value base load power in a reliable, non-polluting and cost-effective way.

7.6. Clean energy

Renewable energy technologies provide an excellent opportunity for mitigation of greenhouse gas emissions and reduce global warming [31]. It is estimated that 300 kg of CO_2 could be avoided for each MWh generated by ocean energy, [32]. Thus, clean energy from the present plant could effectively prevent approximately 17,000 t of CO_2 entering the atmosphere.

8. Conclusions

This paper introduces a new technology that uses hydroelectric power to tap the oceans' enormous energy resource. It discusses the various technical and economical aspects of the design. The benefits of energy provided by OHP can be summarized as follows:

- Because a constantly recharging flow of water provides the energy that the plant exploits to make electricity and water is not used up in the process, it is a clean and renewable energy source.
- Essentially unlimited quantities of renewable energy close to the centers of population and industry. Since the plant uses no fuel, there are no costs of transport, storage, handling or the uncertainties of fuel pricing.
- Reduces dependency on other countries for conventional fuel.
- More environment friendly than conventional hydroelectric plants.
- For conventional fossil-based power plants, the footprint of the plant superstructure, surrounding grounds, etc. can occupy up to 6 sq km of expensive real estate for a 1000 MW plant. A comparable OHP would occupy 3 sq km of effectively free ocean surface out of sight from the shore.
- As a renewable energy technology, it will attract government instituted incentives, which could include accelerated depreciation benefits and Carbon Credits under the Clean Development Mechanism. In USA, new renewable technologies are eligible to receive \$22/MWh production tax credit [33].
- An aggregation of such plants along the coastline, cost effectively supplements the national electrical grid of that country.

References

[1] Ocean Energy Technology. Overview Federal Energy… NREL ⟨http://www.nrel.gov/docs/fy09osti/44200.pdf⟩; 2009 [accessed Jan 2012].
[2] AFdo Falcao. Wave energy utilization; a review of the technologies. Renew Sustainable Energy Rev 2010;14:899–918.
[3] Kathleen McFall, Armistead Tom. Offshore pumping system supplies hydroelectric plant. ⟨http://enr.construction.com/nows/powerIndus/archives/040726.asp⟩; [accessed June 2012].
[4] Alexy Biteryakov. Offshore hydropower station Patent (⟨http://www.google.com/patents/WO2013008108A1⟩; 2013 [accessed Jan 2014].
[5] Falnes JA. A review of wave energy extraction. Mar Struct 2007(20):185–200.
[6] Pontes TM, Falcao A. Ocean energies resources and utilization. In: Proceedings of 18th congress, Buenos Aires; 2001.
[7] Feasibility study severn tidal plant, Department of Energy and Climate Change, Oct 2010. ⟨https://www.gov.uk/…/1_**Feasibility_Study**_Conclusions and_Summary….pdf⟩; [accessed Jan 2014].
[8] Nazir CP. An engineer's guide to invention and innovation. New Delhi: UNICORN BOOKS; 2013; 77–82.
[9] SIHWA TIDAL. ⟨www.british-hydro.org/uploads/1132008110145AM.pdf⟩; [accessed Jan 2014].
[10] Strepy-Thieu Boat Lift. ⟨http://services-techniques.met.wallonie.be/en/bridges_civil_enginering/⟩; 2010 [accessed Dec 2013].
[11] Pumped storage hydroelectricity. ⟨en.wikipedia.org/wiki/Pumped-storage_hydroelectricity⟩.
[12] Collier D. Mallampaya: the first CGS built in Asia. Ove Arup J. UK 2002.
[13] Whitehouse JS, Sutherland J, Harris MJ. Evaluating scour at marine gravity foundations. Proc. ICE Marit Eng 2011;164:143–57.
[14] Jerome HV. Feasibility study of tidal power barrages. Netherlands: T.V. Delft Department of Hydraulic Engineering; 2007; 10–1.
[15] Floating Concrete Structures. Examples from practice. Berne Switzerland: VSL International Ltd; 1992.
[16] Lal J. Hydraulic machines. New Delhi, India: Metropolitan Book Co; 1975; 141.
[17] Green J, Bowen A, Lee JF, Yih-Huei W., Collection and transmission system for offshore wind power, National Renewable Energy Laboratory, Offshore Technology Conference, Houston Texas; 2007, Conf paper NREL/CP 500-41135.
[18] Hydro Help1. ⟨http://www.Hydrohelp.ca/fichiers-a-…/Hydro Help/ProgramDescription.pdf⟩; 2010 [accessed Sep 2013].
[19] Hartman L, Seeley W. SME-Mining Engineering Handbook Vol 2. Technology and Engineering 1992 Mudd Memorial Fund of AMIE. Soc Min, Metall Explor (US) 1992:1653–6.
[20] Concept Study Western Offshore Transmission Grid. ETSU K/EL/00294 ⟨www.berr.gov.uk/files/file15105.pdf⟩; 2011 [accessed Dec 2013].
[21] Typical Capacity Factor of a Hydro electric Power Plant. Jcmiras. Net-02 ⟨http://www.jcmiras.net/surge/p195.htm⟩; 2011 (accessed Dec 2013).
[22] Kreb D, Runte T, Streck G. Planning of the ship lift at the three Gorges Dam. ⟨www.kuk.de/content//akt/pub/173.pdf⟩; 2009 [accessed Nov 2013].
[23] Kai Lund. Technical report on the prefeasibility study for the Popa Hydro Power Project. ⟨http://www.nampower.com.na/pages/paper-about.asp⟩; 2007 [accessed Jan 2013].
[24] National Renewable Energy Lab. Energy Analysis-Simplified Levelized Cost of Energy Calculator ⟨http://www.nrel.gov/analysis/lcoe.html⟩; 2011[accessed Dec 2013].
[25] Baker C. Tidal lagoon generation scheme in swansea bay. A report on behalf of DTI and the Welsh Development Agency ⟨http://www.bis.gov.uk/files/file.30617.pdf⟩; 2011 (accessed Nov 2013).
[26] Chary LR. Offshore wind farms in India an emerging opportunity for marine engineers. MER the Journal of the Institute of Marine Engineers (India) May; 2011; 29–44.
[27] Accelerating Marine Energy (CTC 797) – Carbon Trust. ⟨http://www.carbontrust.com/media/5675/ctc797.pdf⟩; [accessed Jan 2014].
[28] Draft MGD 33.1 Mine winders general requirements NSW. ⟨http://www.resources.nsw.gov.au/_data/assets/pdf../Draft_MDG_33.1.pdf⟩; [accessed Nov 2013].
[29] Mosaic Potash Esterhazy, K2 Mine. ⟨http://\www04.abb.com/global/seitp/seitp202.nsf/D/../Mosaic + case + study.pdf⟩; [accessed Jan 2014].
[30] CJ..Vos. CGS in North Sea ⟨cdn.bam..nl/../25_years_gravity_based_structures-196-1363181985169..⟩; [accessed Jan 2014].
[31] Pamwar NL, Kaushik SC, Kothari S. Role of renewable energy sources in environmental protection: a review. Sustainable Energy 2011;15:1513–24.
[32] International Energy Agency i Implementing Agreement on ocean energy systems. ⟨http://www.wavec.org/client/files/2010_Annual_Report.pdf⟩; Annual Report 2010 [accessed Jan 2014].
[33] US Energy Information Administration. Annual Energy Outlook 2013, Dec 2012, DOE/EIA-0383; 2012.